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Finland

MetNet-seminar
Dokuz Eylül University, Izmir, TURKEY
10-11 October 2012
Kemi-Tornio region in Finnish Lapland

- Pivotal centre for trade and industry in northernmost Europe
  - wood processing
  - mining
  - steel industries
  - machine shop industry
  - electronics and media industry
- 80 000 inhabitants
KTUAS mission

• Degree-awarding education
  Business and Administration
    Bachelor of Business Administration • Master of Business Administration
  Information Communication Technology
    Bachelor of Business Administration
  Engineering and Technology
    Bachelor of Engineering • Master of Engineering
  Health Care and Social Services
    Bachelor of Health Care • Master of Health Care
    Bachelor of Social Services • Master of Social Services
    Bachelor of Geriatric Care • Master of Geriatric Care
  Visual and Media Arts
    Bachelor of Visual and Media Arts

• Research & Development
• Further training and Business services
Engineering and Technology, Research & Development

Materials Usability Research Team

• Research team adapts materials and technology science in solving product development based problems with the industry.

• Our competence areas are:
  • stainless, UHS structural, wear resistance and armour steels
  • cutting, joining, forming and finishing
  • new production technologies and productivity development
  • materials testing & related tool design and specimen preparation (SFS-EN ISO 17025)
  • 3D design, FEM –modelling of plastic deformation
  • proto manufacturing, 3D hydridlaserwelding, pWPS & WPS, hydroforming
Bending properties of some ultra-high-strength steels
Dokuz Eylül University, Izmir, TURKEY
10-11 October 2012

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Vili Kesti
Ruukki Metals Oy
INTRODUCTION

Ultra-high-strength steels (UHSS)

- $R_{p0.2} > 550 \text{ N/mm}^2$
- $R_m > 700 \text{ N/mm}^2$
- Optim® 700 MC Plus: thermomechanically HR + accelerated cooling
- Optim® 700 QL: quenched and tempered
- Optim® 960 QC:
  - Raex® 400: controlled rolling and subsequent direct quenching
  - Raex® 500:
- Fine-grained martensitic or bainitic-martensitic microstructure
- Good strength and toughness properties
INTRODUCTION

Typical method for manufacturing products from UHSS is bending

Calculation of bending force:

Ruukki: \[ F = C \times \frac{R_m \times b \times t^2}{W} \]

Schuler: \[ F = \begin{cases} \frac{b \times t^2 \times R_m}{W} & (W/t \geq 10) \\ \left(1 + \frac{4 \times t}{W}\right) \times \frac{b \times t^2 \times R_m}{W} & (W/t < 10) \end{cases} \]

Trumpf: \[ F = \frac{1.33 \times b \times R_m \times t^2}{W - \left(2 \times \cos 45^\circ \times R_p\right)} \]

C constant 1.2…1.5

R_m ultimate tensile strength (N/mm²)

b bending width (mm)

t sheet thickness (mm)

W diameter of the V-die (mm)

R_p punch radius (mm)
INTRODUCTION
Spring-back and neutral axis

Spring-back angle:

\[ \beta = \alpha_2 - \alpha_1 \]

where:
\( \alpha_1 \) is the bending angle
\( \alpha_2 \) is the bending angle after spring-back

Spring-back ratio:

\[ K = \frac{\Phi_2}{\Phi_1} \]

where:
\( \Phi_1 \) is the arc angle
\( \Phi_2 \) is the arc angle after spring-back

k-factor:

\[ k = \frac{t}{T} \]

where:
T is the thickness
t is the location of the neutral axis
EXPERIMENTAL

Test materials

<table>
<thead>
<tr>
<th>Test material</th>
<th>Nominal thickness (mm)</th>
<th>C Max</th>
<th>Si Max</th>
<th>Mn Max</th>
<th>P Max</th>
<th>S Max</th>
<th>B Max</th>
<th>Cr Max</th>
<th>Ni Max</th>
<th>Cu Max</th>
<th>Mo Max</th>
<th>Ti Max</th>
<th>Al Max</th>
<th>Rp0.2 min N/mm²</th>
<th>Rm min N/mm²</th>
<th>A5 min %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optim 700 MC Plus</td>
<td>10</td>
<td>0.10</td>
<td>0.50</td>
<td>2.10</td>
<td>0.020</td>
<td>0.010</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>700</td>
<td>750-930</td>
<td>15</td>
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<tr>
<td>Optim 700 QL</td>
<td>8 / 10</td>
<td>0.20</td>
<td>0.80</td>
<td>1.70</td>
<td>0.020</td>
<td>0.010</td>
<td>0.005</td>
<td>1.50</td>
<td>0.50</td>
<td>0.70</td>
<td>0.070</td>
<td></td>
<td></td>
<td>690</td>
<td>770-940</td>
<td>14</td>
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<tr>
<td>Optim 960 QC</td>
<td>8</td>
<td>0.11</td>
<td>0.25</td>
<td>1.20</td>
<td>0.020</td>
<td>0.010</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>960</td>
<td>1000</td>
<td>7</td>
</tr>
<tr>
<td>Raex 400</td>
<td>8 / 10</td>
<td>0.25</td>
<td>0.80</td>
<td>1.70</td>
<td>0.025</td>
<td>0.015</td>
<td>0.005</td>
<td>1.50</td>
<td>1.00</td>
<td>0.50</td>
<td></td>
<td></td>
<td>1000</td>
<td>1250</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Raex 500</td>
<td>10</td>
<td>0.30</td>
<td>0.80</td>
<td>1.70</td>
<td>0.025</td>
<td>0.015</td>
<td>0.005</td>
<td>1.00</td>
<td>1.00</td>
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<td></td>
<td></td>
<td>1250</td>
<td>1600</td>
<td>8</td>
<td></td>
</tr>
</tbody>
</table>

Test procedure

- 285 mm wide samples cut from sheet
- One edge painted white
- Various punch radii and diameter of V-die used
- Bending to 90-degree angle
- Bending line parallel to rolling direction
- Force measured during the press
- Spring-back measured by machine vision system developed in KTUAS
- Cross-sectional samples of the bends examined
EXPERIMENTAL

Spring-back measurement

- Bending procedure is imaged
- Measuring method is based on automatic edge finding and line fitting
- Bending angle $\alpha_1$ and bending angle after spring-back $\alpha_2$ are defined with these fitted lines
RESULTS

Bending force

- The measured force increases when the punch radius increases
- Ruukki's and Shuler's eq. no punch radius as a variable -> constant force
- When the radius is large, best equation clearly Trumpf's (Fig. a)
- Calculated forces higher than measured (Fig. b)

\[ F_c = F_m \]
RESULTS

Bending force

Trumpf: \[ F = \frac{1.33 \times b \times R_m \times t^2}{W - (2 \times \cos 45^\circ \times R_p)} \]

Modified Trumpf: \[ F = \frac{0.8 \times b \times R_m \times t^2}{W - (2.5 \times \cos 45^\circ \times R_p)} \]

- \( R_m \): ultimate tensile strength (N/mm\(^2\))
- \( b \): bending width (mm)
- \( t \): sheet thickness (mm)
- \( W \): diameter of the V-die (mm)
- \( R_p \): punch radius (mm)

• Calculated forces equal with measured
Influence of bending width on force

- Influence of width assumed to be linear in equations
- Edges of the sheet reduce bending strength (force)
- The narrower sample, the larger influence
- Test piece width 285 mm
  - In linear or nonlinear range?
RESULTS

Spring-back

Increasing:
• material strength
• punch radius
• diameter of V-die
  ➢ Increased spring-back

Increasing strength and thickness of the material:
  ➢ Larger punch radius and V-die required
  ➢ Very high spring-back values
RESULTS

Bend cross-sections

Examinations:
- Minimum hardness (HV5)
- Thickness
- Location of the neutral axis
- Separation of the plate
- Minimum bend radius

Material: 8mm Optim 700 QL
RESULTS

Bend cross-sections

<table>
<thead>
<tr>
<th>Test material/nominal thickness</th>
<th>Thickness</th>
<th>R_p (mm)</th>
<th>W (mm)</th>
<th>R_min (mm)</th>
<th>A (mm)</th>
<th>t (mm)</th>
<th>T (mm)</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optim 700 MC Plus / 10 mm</td>
<td>10.1</td>
<td>8</td>
<td>18</td>
<td>6</td>
<td>0.3</td>
<td>4.5</td>
<td>9.6</td>
<td>0.42</td>
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<td></td>
<td>13.5</td>
<td>0.3</td>
<td>4.3</td>
<td>9.7</td>
<td>0.44</td>
</tr>
<tr>
<td>Optim 700 QL / 8 mm</td>
<td>8.2</td>
<td>11</td>
<td>25</td>
<td>7.5</td>
<td>0.7</td>
<td>3.5</td>
<td>7.8</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td>18</td>
<td>0.6</td>
<td>3.9</td>
<td>8.0</td>
<td>0.49</td>
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<tr>
<td>Optim 700 QL / 10 mm</td>
<td>10.1</td>
<td>11</td>
<td>25</td>
<td>8</td>
<td>0.3</td>
<td>4.3</td>
<td>9.7</td>
<td>0.44</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>20</td>
<td>0.3</td>
<td>4.5</td>
<td>9.5</td>
<td>0.47</td>
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<tr>
<td>Optim 960 QC / 8 mm</td>
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<td>18</td>
<td>32</td>
<td>11.5</td>
<td>0.7</td>
<td>3.6</td>
<td>7.7</td>
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<td></td>
<td>23</td>
<td>0.4</td>
<td>3.5</td>
<td>7.5</td>
<td>0.47</td>
</tr>
<tr>
<td>Raex 400 / 8 mm</td>
<td>8.1</td>
<td>18</td>
<td>32</td>
<td>13.5</td>
<td>0.5</td>
<td>3.7</td>
<td>7.7</td>
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<tr>
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<td>0.2</td>
<td>3.7</td>
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<td>0.49</td>
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<tr>
<td>Raex 400 / 10 mm</td>
<td>10.3</td>
<td>25</td>
<td>40</td>
<td>17</td>
<td>0.8</td>
<td>4.7</td>
<td>9.9</td>
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<tr>
<td></td>
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<td></td>
<td></td>
<td>32</td>
<td>0.3</td>
<td>4.8</td>
<td>10.0</td>
<td>0.48</td>
</tr>
</tbody>
</table>

- Plate tends to separate from the punch (A)
  - Minimum radius of the bend ($R_{\text{min}}$) smaller than the punch radius ($R_p$)
  - Separation is reduced when the punch radius is increased
- Thicknesses of the sheets are reduced by 0.2…0.5 mm
- k-factor are between 0.42…0.49
  - Neutral axis is located between the centreline and inner surface of the bend
- k-factors decreased when the punch radius decreased
  - Neutral axis has shifted towards the inner surface of the bend
  - Thickness reduction is higher

\[ k = \frac{t}{T} \]
CONCLUSIONS

• Punch radius has an influence on the force
• Trumpf's equation good correlation between measured and calculated forces
  ➢ After modification better correlation, influence of bending width still unknown
• Increase of punch radius, diameter of V-die and strength increase the spring-back
• Spring-back is high with the UHS steels due to:
  • Strength
  • Large punch radii and diameter of V-die required
• k-factor and thicknesses are reduced and separation of the plate increased
  with decreasing punch radius
  ➢ Selection of the correct diameter of the V-die and punch radius very important!
    • No too small or too large punch radius and diameter of V-die
  ➢ Recommendations of the steel manufacturer should be noted carefully!
Thank you for your attention!

Questions?